Division-of-focal-plane spectral-polarization imaging sensor

*Viktor Gruev, Meenal Kulkarni**
Department of Computer Science and Engineering, Washington University in Saint Louis, One Brookings Drive, Saint Louis 63130, Missouri, USA
**mkulkarni@go.wustl.edu*
(314) 935-4760

Abstract

We have designed, fabricated and tested a division-of-focal-plane spectral-polarization imaging sensor by the monolithic integration of aluminum nanowire linear polarization filters to a spectrally sensitive CMOS imaging array. The sensor has a pixel pitch of 5.0 µm and an imaging array size of 168 by 256 pixel elements. Each pixel comprises three layers of vertically stacked photodetectors, each of which has a particular spectral sensitivity. This sensor is novel in that it can perceive co-registered spectral and polarimetric information in real time. In this paper, we present both a theoretical overview of the operation of this imaging sensor as well as experimental measurements from the fabricated sensor.

1. Introduction

The three fundamental properties of the light field are intensity, color and polarization. Today's imaging sensors record the first two properties with high spatial resolution and low noise [1]. The polarization properties of light have typically been ignored because the human visual system is blind to this modality of light [2]. Polarization imaging techniques have proven very useful in gaining additional visual information in optically scattering environments, and in normal environmental conditions [3, 4]. Motivated by the potential advantages of polarization imaging, we have previously developed polarization imaging sensors by integrating micro-polarization filters with CMOS imaging sensors [5-8]. Results from this research in division-of-focal-plane (DoFP) polarization imaging sensors demonstrate the synergy of integrating CMOS technology with optical filters in order to create new sensory devices that can record the polarization properties of light in real time. In this paper, we describe our integration of a CMOS spectral image sensor with aluminum nanowire polarization filters, leading to a novel integrated DoFP polarization imaging sensor which is also spectrally selective in the visible spectrum [9, 10].

This paper is organized as follows: Section 2 provides the theoretical background for the integrated spectral-polarization sensor; Section 3 discusses experimental results of its optical characterization; and Section 4 concludes with a summary.

2. Background

Capturing a scene's linear polarization properties as a function of spectrum is the primary goal of this research. Partially linearly polarized light is common in nature. Circularly polarized light is less common and will not be taken into consideration in this paper. In order to describe partially linearly polarized light, three parameters are used: the intensity of the wave, its angle of polarization (AoP) and its degree of linear polarization (DoLP) [2].

In this paper, we focus on the group of polarization sensors known as division-of-focal-plane (DoFP) polarimeters, which comprise imaging and micropolarization filters on the same substrate [11]. In a DoFP polarization sensor, pixelated aluminum nanowire linear polarization filters at multiple orientations (typically 0^o, 45^o, 90^o and 135^o) are integrated at the focal plane of an imaging array. These enable the capture of the above polarization parameters, as described below. The Stokes polarization parameters are computed using equations (1) – (3).

$$S_0 = 0.5 \times (I_0 + I_{45} + I_{90} + I_{135}) \quad (1)$$

$$S_1 = I_0 - I_{90} \quad (2)$$

$$S_2 = I_{45} - I_{135} \quad (3)$$

Here, I_0, I_{45}, I_{90} and I_{135} are the intensities through polarization filters oriented at 0^o, 45^o, 90^o and 135^o respectively. Using the Stokes' parameters, DoLP and AoP are computed.

The DoLP ranges from 0 (no linear polarization) to 1 (completely linearly polarized light). DoLP is computed via Eq. (4).

$$DoLP = \frac{\sqrt{S_1^2 + S_2^2}}{S_0} \quad (4)$$

The AoP gives the orientation of the plane of oscillation of the incident light. AoP is computed via Eq. (5).

$$AoP = \frac{1}{2}\tan^{-1}\left(\frac{S_2}{S_1}\right) \quad (5)$$

2.1 Stacked photodetector image sensor for spectral detection

On-chip spectral detection is typically achieved using photodiodes and a collection of band-pass optical filters. In traditional color image sensors, the array of photodiodes is covered with color filters arranged in the Bayer pattern, where a neighborhood of 2 by 2 pixels records blue, green and red components of the incident light. In these image sensors, the spectral information computed in the neighborhood of these pixels has inherent limitations. The first limitation is inaccuracy in captured color due to the spatial distribution of the three differently filtered pixels. The color inaccuracy is especially pronounced in highly structured scenes i.e. scenes with high frequency components, such as edges of objects. The second limitation is loss of spatial resolution. The effective resolution of a Bayer pattern image sensor is reduced by a factor of four if interpolation algorithms are not used. Interpolation algorithms are employed in these image sensors in order to partially recover the loss of spatial resolution and to improve the accuracy of color interpretation.

In order to address the loss of spatial information and misinterpretation of spectral information, researchers have introduced vertically stacked photodiode pixels [12, 13]. This technology relies on a basic physical principle of light absorption: shorter wavelengths, such as blue light are absorbed close to the surface of the material (silicon photodetector), while longer wavelengths, such as red light are absorbed deep into the photodetector. Hence, placing photodiode junctions at different depths in the silicon allows different wavelengths to be absorbed [12].

In practice, junctions at depths around 0.2 µm, 0.8 µm and 3.0 µm provide a workable spectral separation for true color imaging. The top photodiode collects charges near the surface that are generated due to blue wavelength; the middle photodiode collects charges due to the green wavelength and the bottom photodiode can deplete well into the substrate to provide response to the red wavelengths. This principle of stacked photodiodes is employed by our choice of spectral imaging sensor. The scanning rate of the entire image array is limited to four frames per second but a subset of the imaging array can be read out at a higher frame rate. For example, an array of 128 by 128 pixels can be read out at 150 frames per second at 12-bit resolution. This high frame-rate readout speed is useful when tracking fast moving objects in a small field-of-view.

3. Optical characterization of integrated spectral-polarization imaging sensor

The spectral imaging array described in Section 2.2 was integrated with pixel-pitch-matched aluminum nanowire polarization filters. This formed a spectral-polarization DoFP sensor, as shown in Figure 1. The integrated sensor has a spatial resolution of 168 by 256 pixels and a pixel pitch of 5.0 µm.

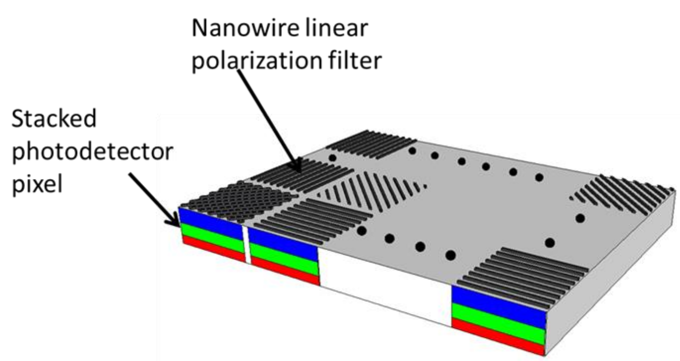

Figure 1: Architecture of the DoFP spectral-polarization sensor

The spectral-polarization sensor was thoroughly optically characterized in order to gauge its polarization and spectral selectivity, as well as properties of the focal plane array, such as the signal-to-noise ratio and linearity. Sections 3.1 and 3.2 show some results from the spectral and polarimetric characterization. Section 3.3 shows real-life spectral-polarization images.

3.1 Spectral responsivity measurements

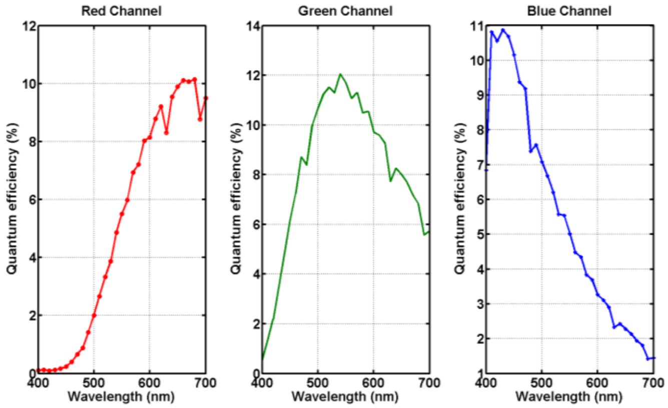

Figure 2: Quantum efficiency for red, green and blue channels.

Using a stimulus of uniform narrowband light, the quantum efficiency of each of the three channels was measured: red, green and blue. The results from these measurements are shown in Figure 2. The spectral selectivity of each spectral channel is clearly demonstrated in these measurements [10]. The red channel has a maximum spectral response at around 700 nm incident light, the green channel responds most at around 550 nm incident light, and the blue channel response is maximum at around 440 nm incident light.

3.2 Polarization responses

We found the sensor to be sensitive to the incident polarization. The polarization responses were measured for each polarization pixel for a 50 by 50 array in each color channel. The stimulus was uniform narrowband polarized light at user-controlled orientation. The results from these measurements for the red channel are shown in Figure 3. The polarization responses follow Malus' Law. Any errors are due to misaligned polarization filters and optical and electrical crosstalk issues [10]. Extinction ratio, which is the ratio of the maximum to the minimum polarization response of the polarization pixel, was found to be a maximum of 6 in the green channel for 550 nm wavelength light. Post instrument calibration, this number rises to 40.

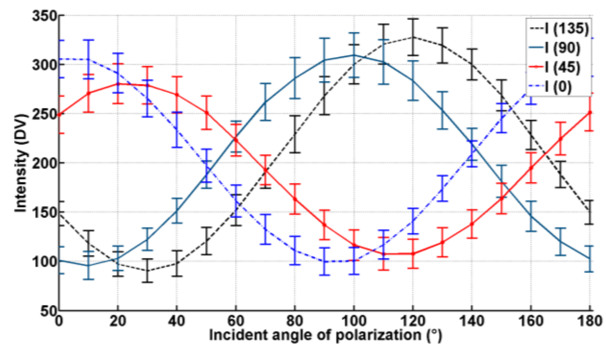

Figure 3: Polarization responses for 50 by 50 I0 array (red channel)

3.3 Spectral-polarization images

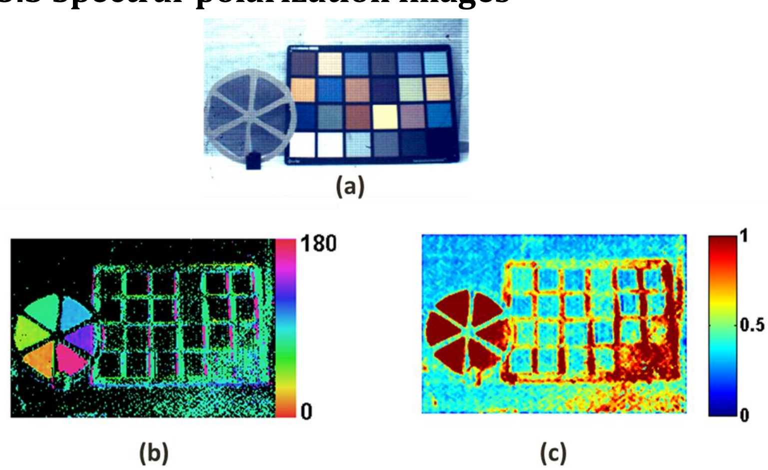

Figure 4: (a) Spectral image, (b) Angle of polarization image, (c) Degree of polarization image, captured simultaneously using the integrated spectral-polarization imaging sensor

Figure 4 shows a real-life spectral-polarization image taken using the integrated spectral-polarization sensor. The image has three parts: spectral image, AoP image, and DoLP image. It is important to note that the entirety of this information is captured in a snapshot and therefore spectral and polarization information is spatially and temporally registered. There are two objects in the image: a Macbeth color checker chart, and a linear polarization filter wheel. The spectral image displays the various colors of the color chart; the polarization images indicate that the polarization filter wheel is indeed polarized. The AoP image shows the various orientations of the linear polarization filters, whereas the DoLP image demonstrates that the filters are highly polarized, with DoLP ~1.

4. Summary

We have presented the design and characterization of a novel imaging sensor capable of perceiving polarization information as a function of the incident spectrum of light in real-time. The sensor has been extensively characterized to determine its spectral and polarization selectivity. The sensor has a maximum measured SNR of 45 dB, average extinction ratio of ~3.5, QE of 12%, and linearity error of 1% in the green channel [10]. Table **1** summarizes the characteristics of the integrated sensor.

Imaging array size	168 by 256
Spectral band	400 – 700 nm
Pixel pitch	5 µm × 5 µm
Temporal resolution	~30 fps
Electron sensitivity	0.06 DV/electron
Quantum efficiency at 550 nm, green channel	12%
Signal to Noise Ratio	45 dB
Average extinction ratio for 0° polarization pixel, green channel	3.5
Linearity error in green channel	1%
Dynamic range	58 dB
Power consumption	250 mW
Size of sensor	2 in. × 3 in. × 5 in.

Table 1: Summary of integrated spectral-polarization image sensor

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